SEA LEVEL FORECASTS AND EARLY-WARNING APPLICATION

Expanding Cooperation in the South Pacific

BY MD. RASHED CHOWDHURY AND PAO-SHIN CHU

THE NEED FOR SEA LEVEL EARLY WARNING IN THE PACIFIC. When many people think of climate change and how it will impact the Pacific Islands, sea level rise is the first thing that comes to their mind. While the sea level rise associated with climate change is a matter of serious concern, the Pacific Islands are also particularly susceptible to the impact of rising sea level on shorter time scales such as year to year variations, with low sea level during El Niño years and high sea level during La Niña years. This variation and associated erosion and inundation are an extremely important issue now, and the Island community must learn how to adapt to this temporal fluctuation in sea level. Because the El Niño–Southern Oscillation (ENSO) phenomena is the most dominant mode of the interannual climate variations in the tropical Pacific Ocean, there has been a demand for ENSO-based advance information on sea level variability on month-to-seasonal time scales.

To address this issue, the Pacific ENSO Applications Climate (PEAC) Center (PEAC Center and PEAC are synonymously used) at the University of Hawaii Manoa (UHM) currently runs the ENSO-based canonical correlation analysis (CCA) statistical model to generate sea level forecasts for the vulnerable U.S-Affiliated Pacific Islands (USAPI) region with lead times of several months or longer (see also www.prh.noaa.gov/peac/sea-level.php; http://pacificcis.org/dashboard/). Note that CCA analysis is a popular statistical method for climate forecasts on month-to-seasonal time scales; this analysis is performed to identify the optimal coupled anomaly pattern relationship between local and large-scale spatial patterns. Also note that the USAPI region is composed of Guam, Saipan, Palau, Republic of the Marshall Islands (RMI) (Majuro, Kwajalein), Federated States of Micronesia (FSM) (the States of Chuuk, Kosrae, Pohnpei, and Yap), and American Samoa (Pago Pago) (Fig. 1). Other than the lone southwest Pacific station at Pago Pago, all stations are located in the northwest Pacific. These Islands are located near the center of activity for major variations in atmospheric and oceanic circulation associated with the ENSO events.

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CURRENT OPERATIONAL SEA LEVEL FORECASTS AT PEAC. Based on the hypothesis that ENSO has a significant impact on climate variability in the Pacific islands, the ENSO state and sea surface temperatures (SSTs) in the tropical Pacific Ocean were initially taken as the primary factors in modulating sea level variability on the seasonal (3–6 months) time scales. The 3–6-month seasonal forecasts have served our clients well in the past; however, the demand for longer lead-time (e.g., 6–12 months) forecasts has increased considerably in order to better support planning and management in climate-sensitive sectors such as water resources, fisheries and aquaculture, agriculture, emergency management, utilities, and coastal zones. Thus, bridging the two time frames (e.g., seasonal and annual outlooks) provides another potential to facilitate smart planning to minimize risk and maximize benefits. This is an important issue for PEAC to address now; it has become more challenging as the skill of the current SST-based CCA forecasts gradually de-

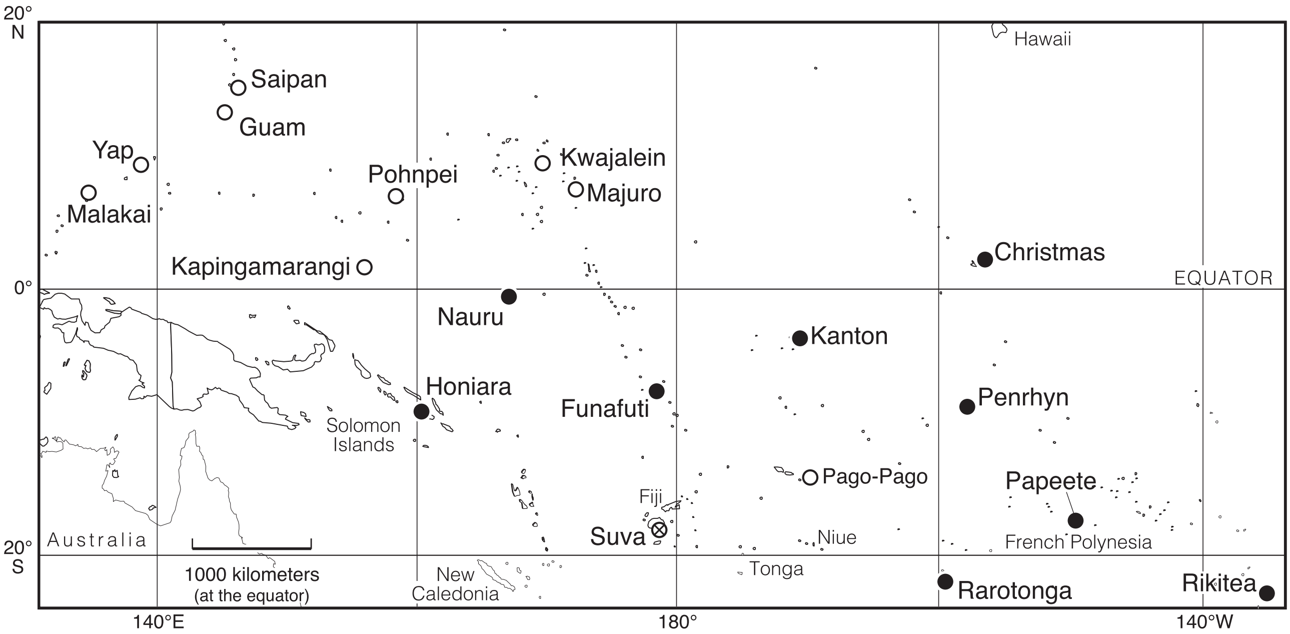

Fig. 1. Map of the Pacific Islands. The USAPI and non-USAPI stations are labeled with open and black circles, respectively. Due to lack of data, non-USAPI station Suva (crossed open circle) could not be processed.

creases as the lead time increases. Therefore, as part of the advances in our operational sea level forecasts, in addition to our previous SST-based endeavors we are now incorporating both SSTs and the zonal wind component of trade winds (U) for modulating sea level variability on longer (i.e., 0–12 months) time scales.

For 6–12-months (or 1–3-seasons) lead time, the combined SST and U-based (henceforth, SST-U) forecasts are found to be more skillful (all are significant at 0.01 level) than the SST-based forecasts alone (Fig. 2). While the SST-based forecasts skills are found to be 0.713, 0.621, 0.529, and 0.468 at 0 to 3-seasons lead, the SST-U-based forecasts skills are 0.757, 0.661, 0.597, and 0.561, respectively, for the same seasons. In short, it showed about 10%–25% improvement for all stations with the exception of Pago Pago, which displayed a marginal decline. However, at three seasons lead (12 months), Pago Pago also showed considerable improvements, as well. Because SST alone does not always reflect coupled mode, the addition of the zonal wind component helps to incorporate the impact of ocean–atmosphere coupling. The other pertinent reason is that the ENSO-related sea level variations in the tropical Pacific are highly connected with thermocline anomalies.

During any normal year, trade winds blow east to west (easterly), which pushes water toward the west via the equatorial ocean currents. In a La Niña year,

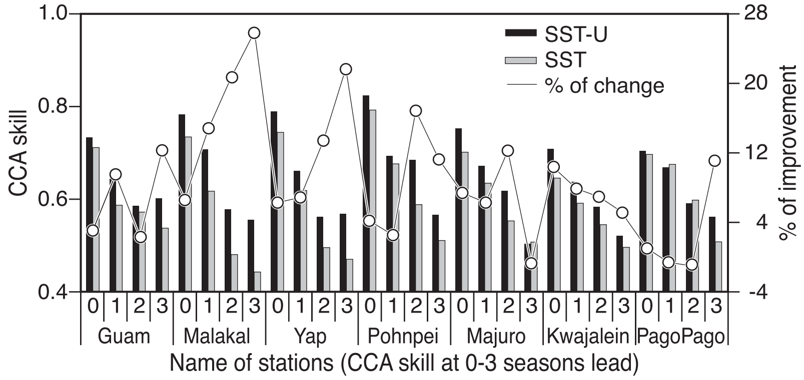

Fig. 2. Average of 4-seasons (i.e., JFM, AMJ, JAS, and OND) correlation coefficient forecast skills (all are significant at 0.01 level) for each of the USAPI stations at 0–3-seasons lead time. Percentage of improvement from the SST-based to SST-U-based forecasts is denoted by the line with circles. Note that any skill above of 0.3 is useful, any skill higher than 0.5 is said to be good, skill higher than 0.6 is considered very good, and skill higher than 0.8 is considered excellent. [Source: Chowdhury et al. (2014)]

trade winds strengthen, and strong upwelling results in relatively cool SST and a shallow thermocline in the equatorial Eastern Pacific. As a result, sea level anomaly in the west Pacific rises (i.e., approximately 0.3–0.5 m). During El Niño years, stronger surface westerly wind anomalies prevail in the equatorial western/central Pacific. Due to the reversal of the prevailing wind direction, piled-up warm water in the tropical western Pacific flows eastward toward South America as triggered by oceanic Kelvin waves and deepens the thermocline off the coast of South America, which causes a rise in sea level in the eastern Pacific. This feature also causes the North Pacific islands to experience lower sea level from July to December during the El Niño–developing year, while the sea level in the South Pacific islands remains unchanged. As the season advances, the band of westerly winds propagates toward the south central tropical Pacific and moves eastward, which causes American Samoa and other South Pacific Islands to experience a lower sea level from January to June for the year following the El Niño–developing year. This causes a 6-month time lag in sea level response to wind fluctuations in the South Pacific, as compared to North Pacific Islands (see also Chowdhury et al. 2007a). This also explains why including wind can lead to better forecast skill, because sea level is controlled by the wind, and thermocline variations are often driven by wind variations by invoking equatorial wave dynamics. Therefore, to further enable our clients in the USAPI region to develop a more efficient, long-term response plan, SST and wind predictors are combined to offer increased capability in sea level forecasting on longer time scales.

To see if there was any significant skill above the persistence forecast, both forecast models (SST and SST-U-based) were compared with a persistence forecast model. At 0-season lead the correlation skill for persistence forecast (0.581) is lower than the SST and SST-U-based models (0.718, 0.758) and the skills of the persistence forecasts drop considerably as the lead time increases from 1 to 3 seasons (6 to 12 months). Therefore, the SST and SST-U-based CCA models are more skillful than persistence forecasts in handling sea level prediction schemes. Our previous experience with SST and persistence-based forecasts also demonstrated similar results.

DATA PREPARATION AND RESEARCH METHODOLOGY. Details of data preparation are available in a 2013 *BAMS* article by Kruk et al. (see also www.pacificstormsclimatology.org); for this paper, our goal is to present very basic information. Hourly sea level station records from the University of Hawaii sea Level Center (UHSLC) Joint Archive for Sea Level (JASL) Research quality dataset and GLOSS/CLIVAR "fast delivery" sea level dataset provided the source of data analysis (http://ilikai.soest.hawaii.edu/uhslc/rqds.html). The Tidal Epoch is defined as the period 1983–2001, and the climatological seasonal cycles are removed from the data. The sea level station extended through this 19-year tidal epoch, and the period of record was at least 30 years in length. The record was at least 80% complete with no more than five missing years and no more than three consecutive missing years. The National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) historical monthly fields of the global SST and zonal wind (U) at 850-hPa are also used. The monthly SST and U data for the tropical region from 30°N to 30°S and 100°E to 100°W are downloaded from the data library of the International Research Institute for Climate and Society (http://iridl.ldeo.columbia.edu/).

The methodology is composed of composite analyses of seasonal variations of SST and trade winds, linear correlation of SST and wind with sea level, empirical orthogonal function (EOF) analysis, and CCA methods to forecast sea level on seasonal time scales. In the combined EOF analysis, the SST and zonal wind (U) fields are weighted equally. Leading EOFs are selected as independent variables for the subsequent CCA model. The leading EOFs of SST and wind anomalies (X-EOFs) were calculated for each season. In our analyses, a total of eight eigenmodes were chosen for the SST and U in the CCA model, and the optimal numbers of EOFs (maximum five) were retained based on the cross-validated skill (see Chowdhury et al. 2014 for details on the research methodology). Sixty-five to sixty-nine percent of total variance was explained by the EOFs of SST and wind analysis. Eighty-eight to ninety-four percent of the total variance was provided by the EOFs of sea level (Y-EOFs) with the first three modes retained.

Using CCA analysis enabled us to identify pairs of patterns of two multivariate datasets (vectors X and Y) and also construct sets of transformed variables by projecting the original data onto the patterns. In this study, X is SST-U and Y is sea level. These new variables maximize the interrelationships between the two datasets. We use a cross-validated scheme with one year withheld to estimate the skill of the CCA model for 1975–2012. Withholding one year is justi-

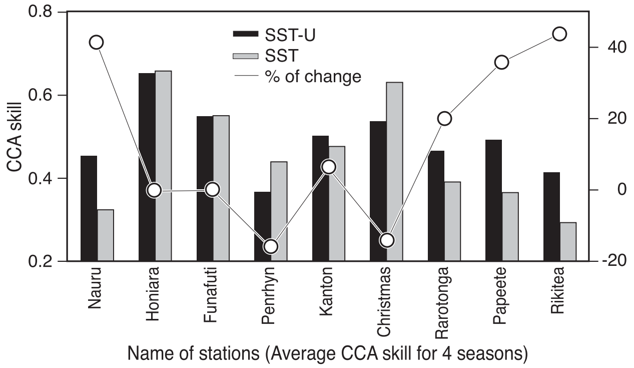

Fig. 3. Same as Fig. 2, except for comparison of skills (average of 0–3-seasons lead forecasts) for non-USAPI stations.

fied when autocorrelations are low, and this is the case for the sea level data (< 0.1) (see also Chowdhury et al. 2014). All data were used with the exception of those collected during the targeted prediction season. We recomputed climatology and redefined the anomaly of the target year using the means of other years. By repeating this procedure many times, we obtain 36 forecasts for sea level that were then compared to the observed sea level. The Climate Predictability Tool (CPT) (http://iri.columbia.edu/our-expertise/climate/tools/cpt/) software is used to generate CCA hindcast results. For a more detailed description of the methodology used, see Chowdhury et al. (2014).

SEA LEVEL FORECASTS: EXPANDING COOPERATION IN THE SOUTH PACIFIC.

In a recent Regional Integrated Water Level Service meeting (held in Honolulu on 10–11 January 2012), discussions among representatives of the National Oceanic and Atmospheric Administration (NOAA), the New Zealand (NZ) National Institute for Water and Atmospheric Research (NIWA) and Met Service, Australia's Bureau of Meteorology (BOM), and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) revealed that development and distribution of "seasonal water level outlooks" in the entire Pacific basin region is an area of mutual interest. The meeting represented a center of action within a broader effort to support regional collaboration of an integrated water level service in the Pacific basin. Therefore, the current USAPI region-focused sea level products were discussed. This product was identified as being instrumental for generating a "sea level outlook" for the non-USAPI region in the southwest Pacific. At PEAC, we were therefore motivated to establish an experimental framework for the development of sea level–related seasonal and annual outlooks tailored toward coastal flooding/erosion risk warning and water resources management for the non-USAPI region. In addition to this, our forecasting experience with Pago Pago was also very informative. We studied 10 southwest Pacific stations; however, one of the stations (i.e., Suva) could not be processed because of insufficient data (e.g., less than 30 years of time series). Finally, we added nine new stations (i.e., Nauru, Honiara, Funafuti, Penrhyn, Kanton, Christmas, Rarotonga, Papeete, and Rikitea) (Fig. 1) to our season-to-annual sea level forecasting scheme. In this paper, we synthesize the current operational forecasting, warning, and response activities of the PEAC Center and discuss the manner in which our experience in the USAPI region can contribute to the development of adaptation strategies for longer time-scale climate variability and change for some of the non-USAPI small islands in the south Pacific.

Figure 3 shows a comparison of SST and SST-U-based CCA cross-validation hindcast skills (averages of 0–3-seasons lead times) for each of the non-USAPI stations. The SST-U-based forecasts displayed considerable improvement for Nauru, Rarotonga, Papeete, Rikitea, and Kanton. Forecasts for Honiara, Funafuti, Penrhyn, and Christmas did not show improvement, and those for Penrhyn and Christmas declined (Fig. 3). It is not clear why the hindcast skills are not similar for all the south Pacific stations and why the additional predictor (U) makes a negative contribution to the predictand; further research is therefore needed. However, a huge number of missing data could be one of the factors for the lack of improvement for Honiara and Funafuti. The other two stations,

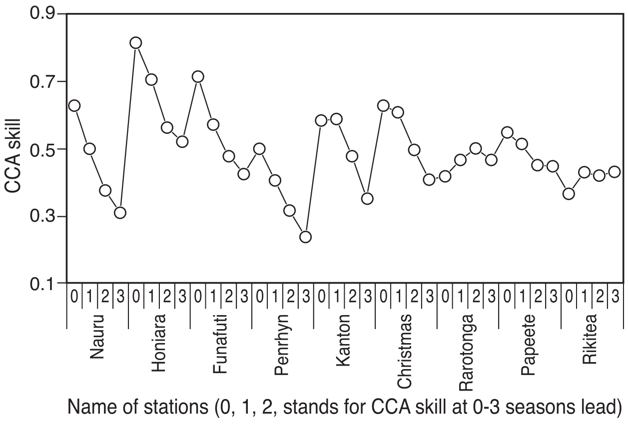

Fig. 4. SST-U-based forecasts for non-USAPI stations (average of 4-seasons skills at 0–3-seasons lead) (see also Fig. 2).

Penrhyn and Christmas, lie between 10°S and 10°N and 180° and 140°W, which is near the nodal line of sea levels linearly related to ENSO. Therefore, in addition to missing data, we speculate that the locations of these two stations are the reason for low skills.

We further examined the SST-U-based forecasts skills for each season for the non-USAPI station. Figure 4 shows average skills for four seasons (i.e., JFM, AMJ, JAS, and OND) at 0–3-seasons lead time. The forecast skills represent the accuracy based on 1975–2013 time series. As evident, different islands show different levels of predictive skill (Fig. 4). Forecasts for Nauru, Honiara, and Funafuti are skillful. Kanton and Christmas displayed moderate skill, while the skill of Penrhyn is relatively weak. Each of these stations show the highest skills with 0-season lead; the skill gradually decreases as the season advances and, similar to the USAPI region, this is somewhat expected in the non-USAPI region. It is also noticeable that, as we move farther south, the forecasting skills for the stations Rarotonga, Papeete, and Rikitea are marginal, and the skill didn't change as the season advanced. One probable reason for the weaker skill of these three stations is their locations, which are farther away from the equator and under the weaker ENSO influence.

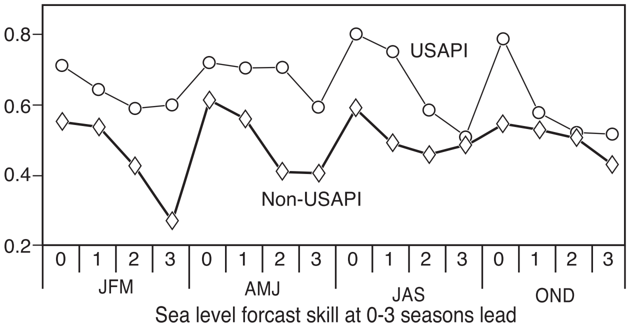

Fig. 5. Comparison of SST-U-based average forecast skills for all non-USAPI and USAPI stations for seasons JFM, AMJ, JAS, and OND at 0–3-seasons lead.

A WAY FORWARD. While the USAPI stations displayed an average skill of 0.638, 0.684, 0.664, and 0.604 (at 0–3-seasons lead forecast) for seasons JFM, AMJ, JAS, and OND (Fig. 5), the skill was found to be 0.450, 0.501, 0.509, and 0.507, respectively, for the non-USAPI region. Therefore, the overall forecast skills for the non-USAPI region are slightly weaker than those for the USAPI region. Among the four seasons, AMJ and JAS exhibited highest average skill for the USAPI stations (see also Chowdhury et al. 2014) while JAS and OND exhibited highest for the non-USAPI stations, respectively. The JAS season probably has better predictability in both regions because ENSO responses are most pronounced during the boreal winter, as the Pacific SST and surface pressure anomalies are more likely to be in phase and reach their peaks during the antecedent boreal winter/spring.

The PEAC forecasts are regularly updated and disseminated through the appropriate channels to our user community. These products are currently fully instrumental to enhance the governance capacity to address disasters in the USAPI region. Therefore, the southwest non-USAPI region may also take advantage of these products to enhance their ability to address disasters.

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